Abstract

Wireless Local Area Networks (WLANs), based on the IEEE 802.11 standard, provide wireless access to the Internet in university campuses, enterprise environments and commercial hot-spots. The wide acceptance of 802.11 technology has already led to high-density unplanned and unmanaged networks in urban areas as well as high-density planned networks in enterprise environments. Efficient design and management of high-density enterprise WLANs is an important research topic. In unplanned and unmanaged WLANs, the objective is to make the networks "self-organizing" and "self-managing." A clear analytical understanding of the behavior of WLANs in various network scenarios could be extremely useful in achieving these objectives.

Our work in this thesis is primarily concerned with analytical modeling of WLANs that are based on the Distributed Coordination Function (DCF) Medium Access Control (MAC) protocol. The DCF provides the fundamental access method in 802.11 WLANs. We have developed accurate analytical models for the following scenarios:

(1) Single cell WLANs with Poisson packet arrivals.

(2) Multi-cell *infrastructure* WLANs with:

  (a) saturated nodes, i.e., when the nodes are always backlogged,

  (b) TCP-controlled *long* file downloads, as in file transfer applications, and

  (c) TCP-controlled *short* file downloads, as in web browsing applications.

We provide a new approach to model single cell WLANs with Poisson packet arrivals. By applying a "State Dependent Attempt Rate" (SDAR) approximation, we model a single cell WLAN with non-saturated nodes as a *coupled queue system*. We provide a sufficient condition under which the joint queue length Markov chain is positive recurrent.

For the case when the arrival rates into the queues are equal, we propose a technique to reduce the state space of the coupled queue system. In addition, when the buffer size of the queues are finite and equal, we propose an iterative method to estimate the stationary distribution of the reduced state process. Our iterative method yields accurate predictions for important performance measures, namely, "throughput", "collision probability" and "packet delay".

We replace the detailed implementation of the MAC layer in NS-2 simulator with the SDAR contention model, keeping all the other layers unchanged, thus yielding a "model-based" simulator at the MAC layer. We demonstrate that the SDAR model of contention provides an accurate model for the detailed CSMA/CA protocol (i.e., for the DCF) in single cells. In addition, since the SDAR model of contention, when applied to NS-2, removes much of the implementation details of the NS-2 MAC layer, we achieve speed-ups of 1.55–5.4 w.r.t. MAC layer operations, depending on the arrival rates and the number of nodes in the single cell WLAN.

To model multi-cell infrastructure WLANs, we consider a restricted network setting where a so-called "Pairwise Binary Dependence" (PBD) condition holds. The PBD condition is a geometric property which enables modeling at the "cell-level". If the PBD condition holds, then the relative locations of the nodes within a cell do not matter. We argue that, in a dense deployment of Access Points (APs), the PBD condition would hold at least approximately. Thus, the PBD condition provides a good starting point for modeling multi-cell infrastructure WLANs with a dense deployment of APs, which are otherwise difficult to model analytically.

Applying the PBD condition, we develop a first-cut scalable cell-level model for multi-cell infrastructure WLANs with arbitrary cell topologies. Unlike a node- or link-level model, the complexity of our cell-level model increases with the number of cells rather than with the number of nodes/links. We first develop our model with saturated nodes and then extend it to TCP-controlled long file downloads. We demonstrate the accuracy of our cell-level model via NS-2 simulations. *We also demonstrate the predictive capability of our cell-level model when the PBD condition does not hold.* We show that, as the “access intensity” of every cell goes to infinity the aggregate network throughput is maximized. Based on this insight, we propose a distributed channel assignment algorithm called “Maximal Independent Set Algorithm” (mISA). The channel assignments provided by mISA are *Nash equilibria in pure strategies* for the objective of maximizing *normalized network throughput.* Also, mISA requires neither topology information nor message passing, and takes only as many iterations as there are channels. In contrast to prior work, our approach to channel assignment is based on the *throughput metric.*

To model multi-cell infrastructure WLANs with TCP-controlled short file downloads we retain the PBD condition, and consider Poisson flow arrivals and i.i.d. exponentially distributed flow sizes. As in the seminal work by Bonald et al. [Sigmetrics, 2008], we model a multi-cell WLAN as a *network of processor-sharing queues with state-dependent service rates.* We exhibit the deficiency in the *service model* proposed by Bonald et al., and identify the implicit assumption in their service model which leads to the deficiency. We propose an improved service model and demonstrate its accuracy. Exact analysis of a network of processor-sharing queues with state-dependent service rates is a difficult problem, in general. We apply an *effective service rate* approximation technique and obtain good approximations for the *mean flow transfer delay* in each cell.

Having established the ability of our service model to better capture the service process in DCF-based multi-cell WLANs (under the PBD condition), we call our service model, *DCF scheduling.* We study the *flow-level stability* of small networks, with single or multiple overlapping *contention domains*, under DCF scheduling. We show that, for networks with a single contention domain DCF scheduling achieves the *maximum stability region.* For networks with multiple overlapping contention domains we provide evidence from customized queueing network simulations and NS-2 simulations to argue that DCF scheduling may not achieve the maximum stability region.